(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
19 April 2001 (19.04.2001)

PCT

(10) International Publication Number
WO 01/27692 A1

(51) International Patent Classification⁷: G02F 1/313, H01S 5/10, G02B 6/12

(21) International Application Number: PCT/IL00/00654

(22) International Filing Date: 15 October 2000 (15.10.2000)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:

132385	14 October 1999 (14.10.1999)	IL
09/478,717	6 January 2000 (06.01.2000)	US
60/232,061	12 September 2000 (12.09.2000)	US

(71) Applicant *(for all designated States except US)*: **LAMBDA CROSSING LTD.** [IL/IL]; Haeshel Street 7, 38900 Caesaria (IL).

(72) Inventors; and
(75) Inventors/Applicants *(for US only)*: **MARGALIT, Moti** [IL/IL]; Hashita Street 21, 30900 Zichron Yaaqov (IL). **ORENSTEIN, Meir** [IL/IL]; Yigal Alon Street 11, 32983 Haifa (IL).

(74) Agent: **REINHOLD COHN AND PARTNERS**; P.O. Box 4060, 61040 Tel Aviv (IL).

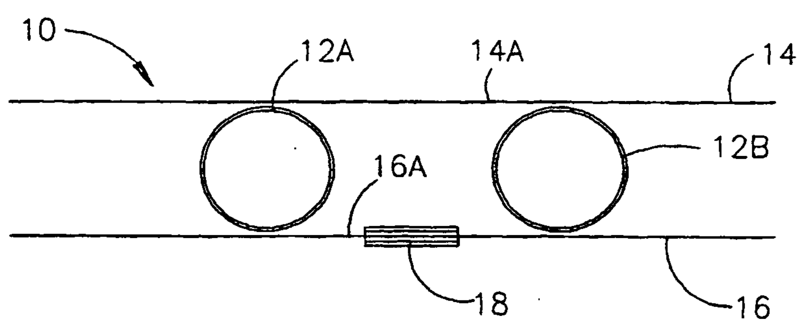
(81) Designated States *(national)*: AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CR, CU, CZ, DE, DK, DM, DZ, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, TZ, UA, UG, US, UZ, VN, YU, ZA, ZW.

(84) Designated States *(regional)*: ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GW, ML, MR, NE, SN, TD, TG).

Published:
— *With international search report.*

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

(54) Title: AN INTEGRATED OPTICAL DEVICE FOR DATA COMMUNICATION



(57) Abstract: An optical device for use in data communication technique is presented. The device comprises a combination of two spaced-apart waveguides and at least two spaced-apart resonator-cavity loops. The resonator-cavity loops are accommodated between the two waveguides and connected to each other through sections of the waveguides in such a manner that the resonator-cavity loops and the waveguide sections create a closed loop compound resonator for storing optical energy of a predetermined frequency range. A control means is used for controlling physical characteristics of the compound resonator to adjust its optical storage characteristics.

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An Integrated Optical Device for Data Communication

FIELD OF THE INVENTION

This invention is generally in the field of optical communication techniques, and relates to an integrated optical device and a method of its manufacture.

BACKGROUND OF THE INVENTION

Optical communication serves as the enabling technology for the information age, and the essential backbone for long haul communication. As this technology progresses, there is a tremendous interest in providing optical routes in the short haul, metropolitan and access networks, as well as in local area networks and cable TV networks. In all these networks, the best of breed solution for bandwidth expansion has been the adoption of wavelength division multiplexing (WDM), which entails the aggregation of many different information carrying light streams on the same optical fiber. A device capable of accessing an individual information stream is fundamentally required in current and future networks. These devices can also add information streams to the optical fiber, as well as impress information on an optical stream by optical modulation.

The basic building block for optical switching is the optical modulator/switch. Various implementations of such a device have been developed, of which the most dominant is the Mach-Zender Interferometer (MZI), in which interference is produced between phase coherent light waves that have traveled over different path lengths. The basic construction of the MZI is schematically illustrated in Fig. 1. Light input to a modulator **1** is via a single-mode waveguide. A beam splitter divides the light into two equal beams that travel through guides **2A** and **2B**, respectively. By applying voltage to electrodes **4**, the effective path lengths can be varied. Hence, optical switching is achieved by creating a phase difference between two arms of the device (guides **2A** and **2B**), and controlling the optical power at the device output.

In general, the performance criteria for the operation of the wavelength routing elements include: the following:

(1) Modulation depth or contrast ratio, which signifies the ratio between two ("ON" and "OFF") or more states of a switch device;

(2) Crosstalk, which defines the ability of the device to select a single optical channel while suppressing information from the other channels;

(3) Electric power consumption;

(4) Modulation bandwidth, which defines the speed at which the switching can be achieved; and

(5) Optical bandwidth within which the modulation is effective.

To achieve a good modulation performance with the MZI, the latter is typically designed with long interference arms. As a result, this device is not efficient in its implementation, and limits the scaling ability of complex optical circuits. Another drawback of MZI-type devices, in their predominant implementation, is their frequency insensitivity over a desired frequency bandwidth. As a result, MZI-type devices cannot be used directly for wavelength routing.

To achieve wavelength routing, the MZI has been utilized in conjunction with wavelength demultiplexers, which provide spatial separation between

different optical frequencies. To this end, a matrix composed of at least N times (N+1) MZI is used to redirect one of the N spatially distinct wavelengths to the device output. The remaining frequencies are recombined using a wavelength multiplexer.

Recently developed integrated electro-optical devices utilize resonant rings to achieve frequency selective switching. Such a device is disclosed, for example, in WO 99/17151. The main components of the device are illustrated in Fig. 2. A resonant ring **6** couples light from one fiber **8a** to another fiber **8b**, when the frequency of the light passing through the fiber **8a** fulfils that of the resonance condition of the ring **6**. By applying an electric field or a thermal source to the ring **6**, its refractive index, and consequently, its resonance condition, can be desirably adjusted. Changing the resonance condition prevents the passage of the previously coupled light and acts as a switch. Alternatively, the loss of the ring waveguide can be changed. Adding loss to the ring diminishes its operation as a resonant cavity, and light cannot be coupled from fiber to fiber.

Unfortunately, the conventional resonant ring based systems require fabrication tolerances that are hard to implement by means of a conventional photolithography technique. This disadvantage becomes more essential in multiple-ring devices, wherein the distance between two locally adjacent rings is a critical factor for the successful operation of the device. The use of a switching mechanism providing de-tuning of a resonant ring out of resonance condition has been proposed, being disclosed for example in WO 98/53535. This solution, however, does not meet the extinction ratio and crosstalk requirements of communication systems.

SUMMARY OF THE INVENTION

There is accordingly a need in the art to improve the operation of electro-optical communication devices by providing a novel electro-optical device, such as an optical frequency dependent switch, a modulator, a laser or amplifier, an Optical Add Drop Multiplexer (OADM), a spectral analyzer, or a sensor.

The optical device according to the present invention utilizes a structure formed by linear waveguides and ring waveguides (resonators). The inventors have found that the use of a ring waveguide provides for a new advantageous feature associated with the following. The conventional integrated optical devices typically employ a small refractive index difference between the waveguide region and the surrounding material. Since optical waveguides can be implemented in complex manners, the universal quantity characterizing the behavior of the confined light is the effective refractive index of the waveguide. In the conventional devices, the difference between the effective refractive index of the waveguide and the index of the surrounding medium is typically smaller then 1%. When using ring micro resonator structures, the effective refractive index of the ring waveguide has to be large, i.e., typically greater then 20%, to accommodate tight mode confinement and small losses. In these structures, however, the effective index of the ring waveguide and the linear waveguide are similar to within 3%. In an integrated optical device according to the present invention, the refractive index of the ring waveguide is at least 20% greater than the refractive index of the linear waveguide that receives an input signal.

The present invention takes advantage of the use of several (at least two) ring resonators. The main idea of the present invention is based on designing an optical complex filter/resonator, wherein waveguide sections are specifically connected to ring resonators in a configuration which enables realization of optical switching, wavelength routing, lasing, wavelength sensitive amplification, optical filtering, etc. The device may also combine a plurality of such filters in a wavelength router module. Generally speaking, the present invention utilizes the collective response of two or more closed loop resonators, which are connected to each other by two or more optical paths, for the purpose of switching or modulating a selected wavelength.

The optical resonator according to the invention is an enclosed cavity aimed at storing optical energy. As compared to the known devices of the kind specified, which utilize a closed-loop type optical resonator, and several such resonators

cascaded in various configurations, the present invention utilizes the inclusion of a feedback path for the optical signal. In other words, in the present invention, the loop resonator serves as a frequency selective mirror within a more complex resonator. These mirrors together with connecting waveguides create closed loop cavities with superior performance and simpler fabrication, and, mainly, are favorable for inclusion of switching capabilities and active media, as compared to the conventional devices.

The wavelength response of a structure composed of several ring resonators coupled to optical waveguides is determined by the physical and geometrical parameters of the resonators and coupling scheme. The present invention provides novel schemes of coupling multiple resonators to achieve predetermined active filtering and modulation characteristics. These coupling schemes are relatively easy to implement, and provide desired modulation characteristics.

There is thus provided, according to one aspect of the present invention, an optical resonator structure for storing optical energy comprising a combination of two spaced-apart waveguides and at least two spaced-apart resonator-cavity loops accommodated between the two waveguides and connected to each other through sections of the waveguides, said at least two spaced-apart resonator-cavity loops and said waveguide sections creating a closed loop compound resonator for storing optical energy of a predetermined frequency range, the physical characteristics of the compound resonator being controllable to adjust the optical storage characteristics of the compound resonator.

The predetermined frequency range is determined by physical and geometrical characteristics of the compound resonator. To control the physical characteristics of the waveguide and/or loop-resonators, a heating means may be used.

One of the two waveguides serves as an input and throughput waveguide, and the other serves as an output waveguide. An optical signal entering the input waveguide may include a plurality of light components having different wavelengths. By actively adjusting the response of the compound resonator, using

a heater or any other means that changes the characteristics of the waveguide sections, one of these wavelengths may be switched from the input to the output waveguide.

According to another aspect of the present invention, there is provided an optical device comprising:

(a) a combination of two spaced-apart waveguides and at least two spaced-apart resonator-cavity loops accommodated between the two waveguides and connected to each other through sections of the waveguides, said at least two spaced-apart resonator-cavity loops and said waveguide sections creating a closed loop compound resonator for storing optical energy of a predetermined frequency range; and

(b) a control means for controlling physical characteristics of the compound resonator to adjust its optical storage characteristics.

The device may comprise additional waveguides and additional loop-resonators, forming together several such frequency selective switches, thereby providing complex optical signal switching and routing.

According to yet another aspect of the present invention, there is provided a laser device where an active material with gain is embedded in at least one of the parts comprising the above-described electro-optical device. This multiple section laser can be controlled by applying the above-described control means to tune its lasing frequency, to q-switch or to passively/actively mode lock the laser device in order to obtain pulsed operation.

According to another aspect of the present invention, there is provided a wavelength router system comprising at least one optical switch and at least one optical filter, wherein the switch and the filter is constructed as the above-described electro-optical device.

According to yet another aspects of the present invention, there are provided the following: an optical spectrum analyzer, an OADM, and a sensor, each, comprising the above combination of two linear waveguides and at least two resonator cavity loops.

The real time monitoring of optical networks poses challenges for spectral analysis systems, such as the need for high resolution, short spectrum acquisition time, low cost. low loss on the optical link, and small size. In standard spectrum analyzers, where the wavelength separation element is based on gratings, high resolution implies larger size and higher cost. An alternative would be to use tunable filters to scan across the optical spectrum of interest. However, existing tunable filters are limited in their ability to provide the required resolution. According to the present invention, a compound cavity, high Q optical ring resonator structure is utilized as a scanning filter, and is used for the analysis of optical spectra.

Modern optical communications are typically based on transmitting frequency multiplexed optical signals through an optical fiber. The OADM is capable of adding or dropping optical channels from an optical fiber, and is an essential element in modern optical communications. In the present invention, the OADM is based on a combination of tunable filters, which provide the add or drop multiplexing functions. Since OADMs have to meet stringent criteria in their filtering, each ring resonator is an optical filter, and, by combining them in parallel, high order filters are obtained.

In general, the resonator-cavity loops (ring-resonators) can be replaced by any other implementation of a frequency-selective element that couple between the two waveguide sections. For example, optical gratings can be used.

According to yet another aspect of the present invention, there is provided an electro-optical device comprising:

- a combination of two spaced-apart waveguides and at least two spaced-apart wavelength-selective elements accommodated between the two waveguides and connected to each other through sections of the waveguides, said at least two spaced-apart wavelength-selective elements and said waveguide sections creating a closed loop compound resonator for storing optical energy of a predetermined frequency range; and

- a control means for controlling physical characteristics of the compound resonator to adjust its optical storage characteristics.

The fabrication technology of waveguides is well developed in many classes and families of materials. The relaxation of the fabrication tolerances in the present invention relates to the possibility of vertical coupling of light from the waveguides to the ring resonators. Since the vertical fabrication tolerances are much better than the horizontal tolerances, the result is a device which is simpler to manufacture. However, the details and design of the invention extend beyond such devices in which only vertical coupling exists between the waveguides and resonators.

Thus, according to yet another aspect of the present invention, there is provided a method for manufacturing the above device utilizing existing lithography techniques.

More specifically. the present invention is used with the ring-resonators and is therefore described below with respect to this application.

BRIEF DESCRIPTION OF THE DRAWINGS

In order to understand the invention and to see how it may be carried out in practice, a preferred embodiment will now be described, by way of a non-limiting example only, with reference to the accompanying drawings, in which:

Fig. 1 is a schematic illustration of the conventional MZI structure;

Fig. 2 is a schematic illustration of the conventional resonant ring based electro-optical device;

Fig. 3 is a schematic illustration of an electro-optical device according to one embodiment of the invention;

Fig. 4 graphically illustrates some advantageous features of the device of Fig. 2, as compared to the conventional devices;

Fig. 5 graphically illustrates simulation results of the operation of the device of Fig. 2;.

Figs. 6a to 6c schematically illustrate electro-optical devices according to three different embodiments of the invention, respectively, suitable for designing complex filter structures;

Figs. 7a to 7c illustrate three more examples, respectively, of complex filter structures constructed according to the invention;

Fig. 8 graphically illustrates the operational principles of the devices of Figs. 7a-7c;

Fig. 9 sche4matically illustrates a block diagram of a wavelength router system utilizing the devices according to the invention;

Fig. 10 illustrates a system utilizing the optical switches and filters according to the invention, and using ASE for monitoring the status of the optical switches;

Figs. 11A and 11b illustrate main constructional features and main functional features, respectively, of a single channel Optical Add Drop Multiplexer (OADM) according to the invention;

Fig. 12 graphically illustrates the spectral response of one-, two- and three-ring filters for use in an OADM;

Fig. 13 schematically illustrates a four port add drop multiplexer;

Fig. 14 schematically illustrates the integration of switches and add drop filters for switch-able filters;

Fig. 15 illustrates the main components of a spectral analysis filter and detector according to the invention;

Fig. 16 illustrates a tap coupler and spectral analysis system utilizing the filter of Fig. 15;

Fig. 17 illustrates a spectrum analyzer using several spectral filters of Fig. 15; and

Figs. 18 and 19 illustrate the main principles of a sensor device according to the invention.

DETAILED DESCRIPTION OF A PREFERRED EMBODIMENT

Figs. 1 and 2 illustrate conventional MZI-type and ring-resonator type structures, respectively.

Referring to Figs. 3a and 3b, there is illustrated an electro-optical device, generally designated **10**, constructed and operated according to one embodiment of the invention. The device **10** includes a compound resonator, which, according to the present example, is composed of two ring-resonators **12A** and **12B** (constituting resonator-cavity loops functioning as frequency-selective elements), and two waveguides **14** and **16**, wherein waveguide sections **14A** and **16A** connects the rings **12A** and **12B** to each other. As shown in Fig. 3b by way of a block-diagram, these waveguide sections **14A** and **16A** present a spacer S between optical cavities defined by two ring-resonators **R**.

Further provided in the device **10** is a heater element **18** (electrodes) placed on either one of the waveguide sections – the section **16A** in the present example. The operation of the heater element **18** enables to control the refractive index and, consequently, the optical phase imparted by the waveguide spacer S. Generally speaking, the change in the refractive index will induce the required phase shift to change the frequency response of the compound resonator. Such an active phase affecting may be achieved by applying any suitable thermo-optic, piezo-electric, electro-optic or the like effects within the spacer or ring resonator regions.

The device **10** may be implemented as a multi-layer optical structure manufactured by a lithography technique. All the elements of the compound resonator, i.e., the ring-resonators and the waveguides, may be formed in the same optical layer. Alternatively, the compound resonator may be manufactured as a multi-layer structure, namely the waveguides may be located in a locally adjacent upper or lower layer with respect to the layer containing the ring-resonators. This facilitates the manufacture to meet the requirements for small spaces between the coupling elements (i.e., ring and waveguide).

The optical cavities (ring-resonators) are weakly coupled to the waveguides. Direct coupling between the two resonators is not required by this scheme. Each of

the optical cavities is capable of supporting several resonance frequencies, which are determined by the geometrical and material details of the cavity. In the present example of Figs. 3a and 3b, which is the simplest case utilizing a pair of ring-resonator cavities, the two cavities **12A** and **12B** are identical, namely tuned for the same frequency range of the resonance condition. A change in the refractive index of one of compound resonator's elements (which is the waveguide **16** in the present example, since the heating element **18** is associated with this waveguide), will cause changes in the roundtrip phase of the entire cavity, thereby shifting the resonance condition.

As indicated above, although the ring-resonators are exemplified here, any other implementation of the frequency-selective elements (mirrors) that couple between the two waveguide sections may be employed in the compound resonator for the purposes of the present invention. Such a frequency-selective element may, for example, be an optical grating.

Assuming that the waveguide **14** is an input waveguide, and the waveguide **16** is an output waveguide, the response of the compound resonator **10** is essentially different from that of the conventional single-ring resonator shown in Fig. 2. This is illustrated in Fig. 4, showing two graphs $\mathbf{G_1}$ and $\mathbf{G_2}$, presenting optical power **P** at the output waveguide (fiber) **16** as a function of a normalized wavelength λ_{nor}, corresponding, respectively, to the conventional device and device **10** constructed according to the invention. It is self evident that the filtering characteristics and out of band signal suppression of the coupled resonator **10** are much better then those of the conventional single-ring resonator.

Fig. 5 illustrates simulation results of the operation of the device **10**. Three graphs $\mathbf{H_1}$, $\mathbf{H_2}$ and $\mathbf{H_3}$ present the output power **P** of the device **10** as a function of normalized wavelength λ_{nor} for different phase shifts: $\varphi=0$, $\varphi=\pi/4$ and $\varphi=\pi/2$, respectively.

Each of the ring-resonators (two in the present example) is comprised of a waveguide with the index or refraction (n_{core}) larger than its surrounding material ($n_{cladding}$). The waveguide is fashioned into a closed path. called "ring". The input

waveguide passes below the ring-resonators in a manner to allow the overlap of the two waveguide modes and allow for transferring optical power from the input waveguide to the ring-resonator. As for the output waveguide, it is also placed so as to attain the coupling to the ring. This output waveguide may serve as the output of the selected frequency. Alternatively, when the device **10** is to be used as a modulator, this waveguide can also serve as a throughput port for optical frequencies different from that of the modulated signal.

In general, integrated optical elements are composed with contradictory requirements. For low loss and ease of coupling to the external optical fiber, waveguides are realized using a small difference between the refractive indices of the core and cladding. However, to achieve compact structures, tight bends are required which imply a large difference between the refractive indices of the core and cladding. An important result of the current invention relates to the ability to combine the best of both worlds by using ring resonators realized in a high index core and coupled to a low index waveguide. According to the present invention, if, for example, the refractive index of a surrounding medium is 1.46, and the refractive index of an "input" linear waveguide (e.g., **14**) is 1.48, the refractive index of each of the ring resonators **12A** and **12B** can be about 2 and would provide successful operation of the device **10**. Generally, the refractive index of the ring waveguide should be at least 20% greater than the refractive index of the "input" waveguide **14**, to realize low loss small radius ring resonators.

The operation of the device **10** is characterized by the low loss propagation of the optical mode in the ring waveguide. This is achieved by utilizing a refractive index contrast between the waveguide and surrounding material. The ring may be composed of optical glass with a refractive index of about 1.6-1.9, may be made from silicon (refractive index of 3.5) or a layered-structure made of suitable materials such as used in Vertical Emitting Cavity Lasers (VECSELs). It is known that the ring itself manifests on frequencies corresponding to its resonance condition. The resonant frequency of the ring, f_0, is given by:

$$f_0 = \frac{Mc}{2\pi R n_{ef}} \qquad (1)$$

wherein R is the ring radius measured from the center of the ring to the center region of the ring waveguide; n_{ef} is the effective refractive index of the ring waveguide; M is an integer value; and c is the speed of light propagation in vacuum. The effective refractive index can be determined by various known techniques.

One of the important parameters defining the characteristics of the entire device **10**, is the coupling between the ring and the waveguide, since it determines the optical bandwidth and photon lifetime, and, consequently, the modulation efficiency. The power exchange between the waveguide and the ring is denoted by k^2, and can be calculated by computing the overlap integral of the modes of the ring and waveguide multiplied by the interaction length. The optical bandwidth, Δf, is then determined as follows:

$$\Delta f = \frac{k^2 f^2}{2\pi^2 R n_{ef}} \qquad (2)$$

As seen in Fig. 3b, the individual ring-resonator actually presents a two-port device. The throughput function describing the ring optical amplitude characteristics is given by:

$$T(\omega) = \frac{1}{\sqrt{1-k}} \frac{(1-k)(1-e^{j\omega t})}{1-(1-k)e^{j\omega t}} \qquad (3)$$

while the drop function is given by:

$$D(\omega) = -\frac{k}{1-(1-k)e^{j\omega t}} \qquad (4)$$

Here, ω is the radial frequency given by: $\omega = 2f$.

The matrix describing one ring is given by:

$$M_{Ring} = 1/T\begin{bmatrix} 1 & -D \\ D & T^2 - D^2 \end{bmatrix} \qquad (5)$$

Complex structures can be obtained by multiplying the matrixes of the corresponding sections. This calculation technique is known *per se*, and is used in analyzing complex distributed feedback lasers.

Turning back to Fig. 3a, it should be understood that, if at least one of the frequency-selective elements (ring resonators) **12A** or **12B** or at least one of the waveguide sections **14A** or **16A** is filled with an active medium, the device **10** can operate as a laser.

As known, an optical communication system typically requires stringent switching and routing. A single resonant ring device usually cannot meet these requirements. To this end, according to the present invention, filters are designed either as single stage coupled compound resonators, or as multiple-stage coupled compound resonators. Compound resonators of such filtering devices are illustrated in Figs. 6a-6c, being designated **20**, **30** and **40**, respectively. Each of these devices utilizes the compound resonator structure **10** of Fig. 3a as a frequency selective switch/modulator, in which the ring-resonators **R** are coupled both in the forward and back directions, thereby increasing the degrees of freedom in the design of filters. It should be understood that, in all the examples, the matrix model is used in the synthesis and analysis of the filter/switch/modulator characteristics.

In the example of Fig. 6a, the entire waveguide cavity is formed by waveguides **14** and **16**, and three pairs of ring-resonators $\mathbf{R_1}$-$\mathbf{R_2}$, $\mathbf{R_3}$-$\mathbf{R_4}$ and $\mathbf{R_5}$-$\mathbf{R_6}$ enclosed therebetween. In the example of Fig. 6b, a multi-stage coupled compound resonator **30** is composed of two pairs of rings $\mathbf{R_1}$-$\mathbf{R_2}$ and $\mathbf{R_3}$-$\mathbf{R_4}$ enclosed between waveguides $\mathbf{W_1}$ and $\mathbf{W_2}$, and an additional ring-resonator $\mathbf{R_5}$ coupled to an additional waveguide $\mathbf{W_3}$. A multi-stage coupled compound resonator **40** (Fig. 5c)

comprises two compound resonators **10**, and two additional ring-resonators $\mathbf{R_5}$ and $\mathbf{R_6}$, the latter being is coupled to an output waveguide $\mathbf{W_4}$. By appropriately adjusting the index of the waveguide in the corresponding compound resonator, the desired wavelength may be switched from the input to the output waveguide.

Reference is now made to Figs. 7a-7c and 8, illustrating the main constructional and operational principles of three other devices **50**, **60** and **70**, respectively, that are capable of operating as a switch or modulator. The devices **50**, **60** and **70** have somewhat different design of waveguides and rings arrangement. as compared to the previously described examples, as illustrated in the figures in a self-explanatory manner using the same reference numbers for identifying those components, which are common in all examples.

Fig. 8 shows three graphs $\mathbf{D_1}$, $\mathbf{D_2}$ and $\mathbf{D_3}$, corresponding to simulation results of the operation of the devices **50**, **60** and **70**, respectively. Each graph presents the optical power **P** at the output fiber ($\mathbf{W_3}$, $\mathbf{W_3}$ and $\mathbf{W_4}$, respectively) as a function of a phase shift φ in the waveguide section. As clearly seen in the figure, for very small values of the phase shift φ, more then 20dB of signal extinction is obtained. This enables the size required by the waveguide sections to be to significantly reduced, since the optical phase shift is accumulated over the length of the waveguide.

The advantages of the device according to the invention are thus self-evident. The device attains attractive modulation characteristics, requires very small phase shifts, and, consequently, the interaction region, as well as the switching power, can be minimized. The extinction ratio of the optical signal meets optical communication standards.

Fig. 9 illustrates a block diagram of a system **100** utilizing the above-described devices to form a wavelength router. The system comprises three switches $\mathbf{SW_1}$, $\mathbf{SW_2}$ and $\mathbf{SW_3}$, and two filter units $\mathbf{FU_1}$ and $\mathbf{FU_2}$. Each of the filter units is accommodated between two locally adjacent switches, and is designed so as to, when being actuated, route a specific optical frequency. In this example, one of the filters is activated at a time, thereby enabling the routed wavelength to be dynamically chosen. Obviously, a plurality of switching mechanisms can be used

to increase the number of drop ports. It is important to note that this technique requires a considerably lower number of switches than that of the MZI switching matrix. Indeed, for an N-channel, M-drop system, the MZI switching matrix would require at least $(N+M)$ by N matrix, while the system according to the present invention would require N switches with an M by M matrix.

The present invention can also be used for actively monitoring the switch performance. As is known, one the crucial issues in modern communication systems is the status of the on-line switches. A non-operative switch in either the "ON" or "OFF" position can degrade the performance of the communication network. Modern communication systems utilize an erbium-doped fiber to compensate for losses in the optical fiber, connectors and devices. The amplifier emits amplified spontaneous emission (ASE) in all optical frequencies, which are off interest.

In the present invention, it is proposed to use an ASE for monitoring the status of the optical switches. This concept is illustrated in Fig. 10, showing a system **200** that utilizes the components of the above-described system **100**, and two photodetectors $\mathbf{PD_1}$ and $\mathbf{PD_2}$. Each photodetector is placed at the output of the corresponding switch and is coupled to a control unit (monitor) **CU** that monitors the optical power though this switch. Since the ASE exists at all frequencies, it can be used to monitor and control the switches.

The combination of two ring waveguides accommodated between and coupled to the two linear waveguides may be advantageously utilized in various optical devices. Referring to Figs. 11A and 11b, there are illustrated main constructional features and main functional features, respectively, of a single channel Optical Add Drop Multiplexer (OADM), generally designated **300**.

The OADM **300** is composed of two compound resonators **310** and **312**, each constructed as described above, namely, including two ring-resonators accommodated between and coupled to two linear waveguides. Here, each ring resonator is an optical filter, and, by combining them in parallel, high order filters

are obtained. The drop port (filter) is implemented using a double filter pass, while the add port is obtained with a single filter.

It should be noted that the number of rings per functional filter may differ to accommodate the specifications of a particular optical network. This concept is illustrated in Fig. 12 showing graphs **G_1**, **G_2** and **G_3** corresponding to the optical spectral response of, respectively, one-, two- and three-ring filters.

Fig. 13 illustrates a four port add drop multiplexer. Here, multiple channel OADMs are obtained by cascading the structures of Figs. 11A-11B.

Fig. 14 illustrates an example of the integration of switches and add drop filters for switch-able filters. Here, optical switches are added to insert and extract the ring based OADM from the optical path.

Reference is now made to Fig. 15 illustrating the main components of a system **400** formed by a spectral analysis filter **410** and detector **412**. The filter **410** comprises two compound resonators **410A** and **410B** connected in parallel through a common linear waveguide **W_2**, and serves as a compound high Q optical ring resonator structure. The output linear waveguide **W_3** of the structure is connected to the detector **412**. The Q of the filter is determined by the coupling factor describing the amount of light that is coupled into the filter at every round trip. The Q factor is also determined by the optical losses in the cavity and the ring radius.

Fig. 16 illustrates a tap coupler and spectral analysis system, generally designated **500**, utilizing the above-described system **400**. The filter **410** is connected to an optical network (link) **512** via a coupler **514**, which taps a small amount of light, thereby minimizing the losses incurred in the optical link.

Fig. 17 illustrates a spectrum analyzer **600** utilizing several spectral analysis filters – three such filters **610A**, **610B** and **610C** in the present example, used in parallel through a common input linear waveguide **W_1**. Each filter has a different radius, as compared to the others, and therefore is capable of carrying out a different spectral analysis. This feature is associated with two problems that may occur when using ring resonators, namely, limited tuning range and limited free

spectral range. resulting in that a different approach has to be adopted to scan across a wide spectrum.

Turning now to Fig. 18, there is illustrated a sensor device **700** according to the invention. The sensor device **700** comprises an environmental sensitive filter **710** constructed as the above-described compound resonator, which is connected to a laser **712** and a detector **714** through its input and output waveguides $\mathbf{W_1}$ and $\mathbf{W_2}$, respectively. Such a high Q optical filter structure is used as a sensor, which is suitable for various applications, such as a biological, mechanical, or temperature sensor. This is due to the fact that the filter characteristics depend on the external element to be measured.

Fig. 19 shows the results of tuning the laser **712** to the edge of the filter **710**. Generally speaking, the environmental element changes the resonance frequency of the filter, which results in a change of the optical power at the detector. With proper calibration, this device can be used to measure or monitor various physical, mechanical or biological environmental changes.

Those skilled in the art will readily appreciate that various modifications and changes can be applied to the preferred embodiment of the present invention as herein before exemplified without departing from its scope defined in and by the appended claims. In the method claim which follow, characters which are used to designate claim steps, are provided for convenience only and do not apply any particular order of performing the steps.

CLAIMS:

1. An optical resonator structure for storing optical energy comprising a combination of two spaced-apart waveguides and at least two spaced-apart resonator-cavity loops accommodated between the two waveguides and connected to each other through sections of the waveguides, said at least two spaced-apart resonator-cavity loops and said waveguide sections creating a closed loop compound resonator for storing optical energy of a predetermined frequency range, the physical characteristics of the compound resonator being controllable to adjust the optical storage characteristics of the compound resonator.

2. The structure according to Claim 1, wherein each of the at least two resonator cavity loops is designed like a ring waveguide.

3. The structure according to Claim 2, wherein the refractive index of each of the ring waveguides is at least 20% greater than the refractive index of the waveguide serving as an input and throughput waveguide.

4. An electro-optical device comprising the structure constructed according to Claim 1, and a control means for controlling physical characteristics of the structure to adjust its optical storage characteristics.

5. The device according to Claim 4, wherein said control means are placed on either one of the waveguide sections.

6. The device according to Claim 4, wherein said control means are placed on either one of the resonator cavities.

7. The device according to Claim 4, wherein said control means comprises heating means.

8. The device according to Claim 4, wherein said control means comprises electro-optic means.

9. The device according to Claim 4, wherein said control means comprises piezo-optic means.

10. The device according to Claim 4, functioning as a switch.

11. The device according to Claim 4, functioning as a modulator.

12. The device according to Claim 4, wherein the resonator-cavity loops and the waveguides are arranged within same optical layer.

13. The device according to Claim 4, wherein the resonator cavity loops are arranged within same optical layer, and the waveguides are arranged in a locally adjacent layer.

14. The device according to Claim 4, and also comprising at least one additional pair of resonator-cavity loops, all the resonator cavity loops being aligned in line between the two waveguides.

15. The device according to Claim 4, and also comprising at least one structure composed of at least one additional resonator-cavity loop coupled to the compound resonator through one of said two waveguides, and an additional waveguide coupled to said at least one additional resonator-cavity loop.

16. The device according to Claim 15, comprising a plurality of said structures, forming together a plurality of frequency selective switches, thereby providing complex optical signal switching and routing.

17. The device according to Claim 4, wherein said resonator-cavity loops are filled with an optically active medium providing optical gain, the device thereby operating as a laser or amplifier.

18. The device according to Claim 4, wherein said waveguide sections are filled with an optically active medium providing optical gain, the device thereby operating as a laser or amplifier.

19. The device according to Claim 11, wherein said resonator-cavity loops are filled with an optically active medium providing optical loss.

20. The device according to Claim 11, wherein said waveguide sections are filled with an optically active medium providing optical loss.

21. The device according to Claim 15. wherein each of the resonator-cavity loops is a ring-like optical fiber, the optical fibers being combined in parallel through said one of said two waveguides, the device being thereby operable as an Optical Add Drop Multiplexer.

22. The device according to Claim 15, and also comprising a detector connected to said additional waveguide, the device being thereby operable as a spectral analysis filter.

23. The device according to Claim 4, and also comprising a light source and a detector coupled to said structure through its input and output waveguides, respectively, the device thereby operating as an environmental sensitive filter.

24. An electro-optical device comprising:

(a) a combination of two spaced-apart waveguides and at least two spaced-apart resonator-cavity loops accommodated between the two waveguides and connected to each other through sections of said waveguides, said at least two spaced-apart resonator-cavity loops and said waveguide sections creating a closed loop compound resonator for storing optical energy of a predetermined frequency range; and

(b) a control means for controlling physical characteristics of the compound resonator to adjust its optical storage characteristics.

25. A laser device comprising a combination of two spaced-apart waveguides and at least two spaced-apart resonator-cavity loops accommodated between the two waveguides and connected to each other through sections of the waveguides, said at least two spaced-apart resonator-cavity loops and said waveguide sections creating a closed loop compound resonator for storing optical energy of a predetermined frequency range, wherein at least one of said resonator-cavity loops or said waveguide sections is filled with an optically active medium providing gain.

26. A controlled laser device comprising:

- a combination of two spaced-apart waveguides and at least two spaced-apart resonator-cavity loops accommodated between the two waveguides and connected to each other through sections of said waveguides, said at least two spaced-apart resonator-cavity loops and said waveguide sections creating a closed loop compound resonator for storing optical energy of a predetermined frequency range, wherein at least one of said waveguide sections or said closed

loop resonators is filled with an optically active medium providing gain effect; and

- a control means for controlling physical characteristics of the compound resonator to adjust its optical storage characteristics.

27. The device according to claim 26, wherein said control means is used to passively or actively mode locking said controlled laser.

28. The device according to claim 26, wherein said control means is used to Q-switch said controlled laser.

29. A wavelength router system comprising at least one optical switch and at least one optical filter connected to an output of said at least one optical switch, wherein each of the switch and the filter comprises a combination of two spaced-apart waveguides and at least two spaced-apart resonator-cavity loops accommodated between the two waveguides and connected to each other through sections of the waveguides, the resonator cavities and the waveguide sections creating a closed loop compound resonator for storing optical energy of a predetermined frequency range, a control means being provided for controlling physical characteristics of the compound resonator to adjust its optical storage characteristics.

30. The system according to Claim 29, and also comprising a control unit including at least one photodetector connected to said output of the switch for monitoring the status thereof.

31. An integrated electro-optical device comprising:

- a combination of two spaced-apart waveguides and at least two spaced-apart wavelength-selective elements accommodated between the two waveguides and connected to each other through sections of the waveguides, said at least two spaced-apart wavelength-selective elements and said waveguide sections creating a closed loop compound resonator for storing optical energy of a predetermined frequency range; and

- a control means for controlling physical characteristics of the compound resonator to adjust its optical storage characteristics.

32. The device according to Claim 31, wherein said frequency-selective elements are gratings.

33. A method for manufacturing an electro-optical device comprising a combination of two spaced-apart waveguides and at least two spaced-apart resonator-cavity loops accommodated between the two waveguides and connected to each other through sections of the waveguides, the resonator cavities and the waveguide sections creating a closed loop compound resonator for storing optical energy of a predetermined frequency range; and a control means for controlling physical characteristics of the compound resonator to adjust its optical storage characteristics, the method comprising the steps of:

(i) performing a first lithography process to form said at least two spaced-apart resonator-cavity loops in a first optical layer; and

(ii) performing a second lithography process to form the two waveguides in a locally adjacent optical layer.

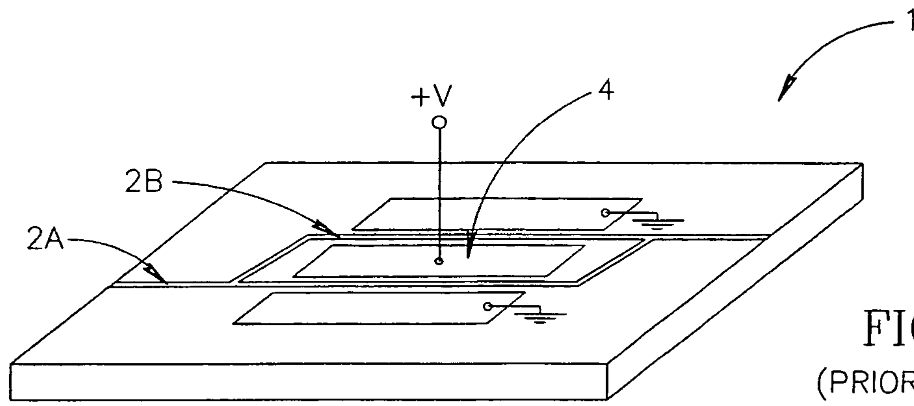


FIG.1
(PRIOR ART)

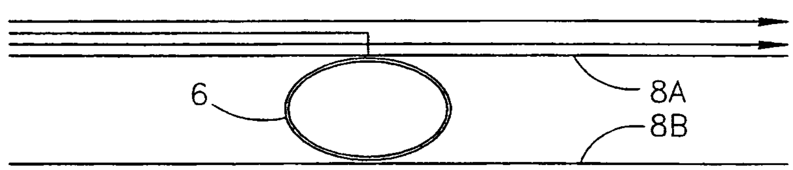


FIG.2
(PRIOR ART)

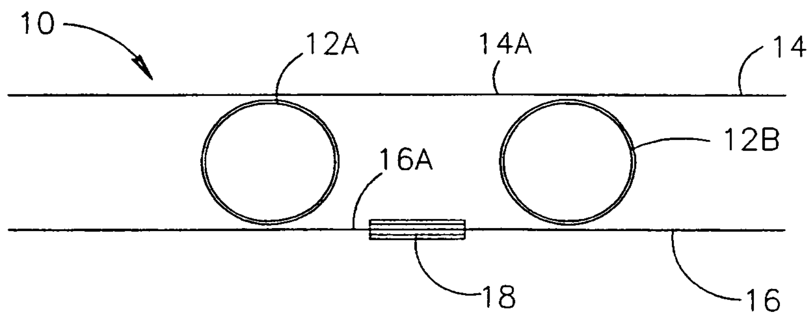


FIG.3A

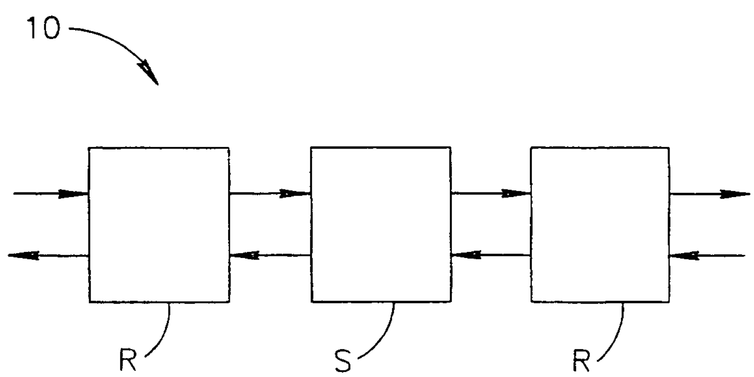
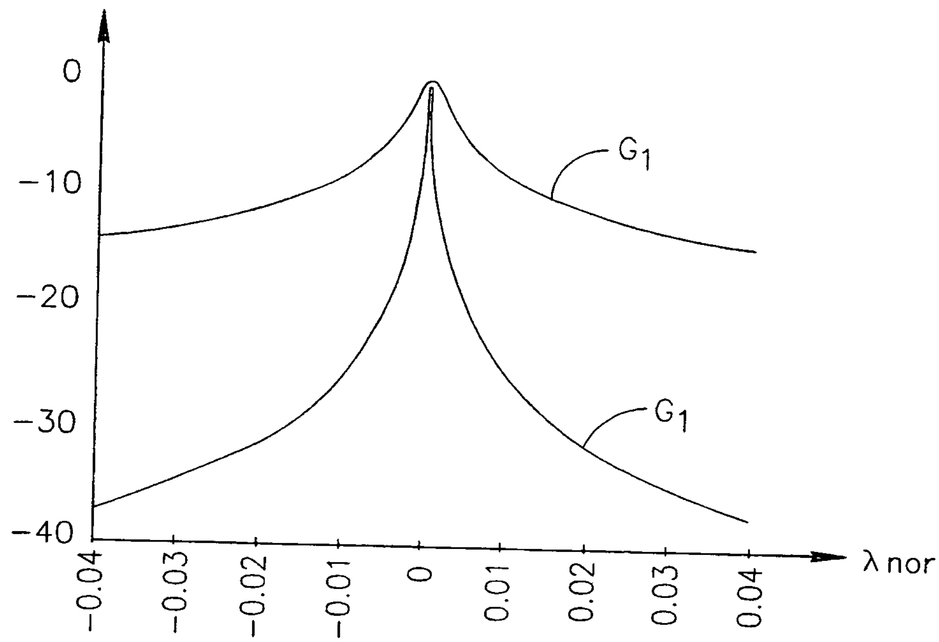


FIG.3B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G1
G1
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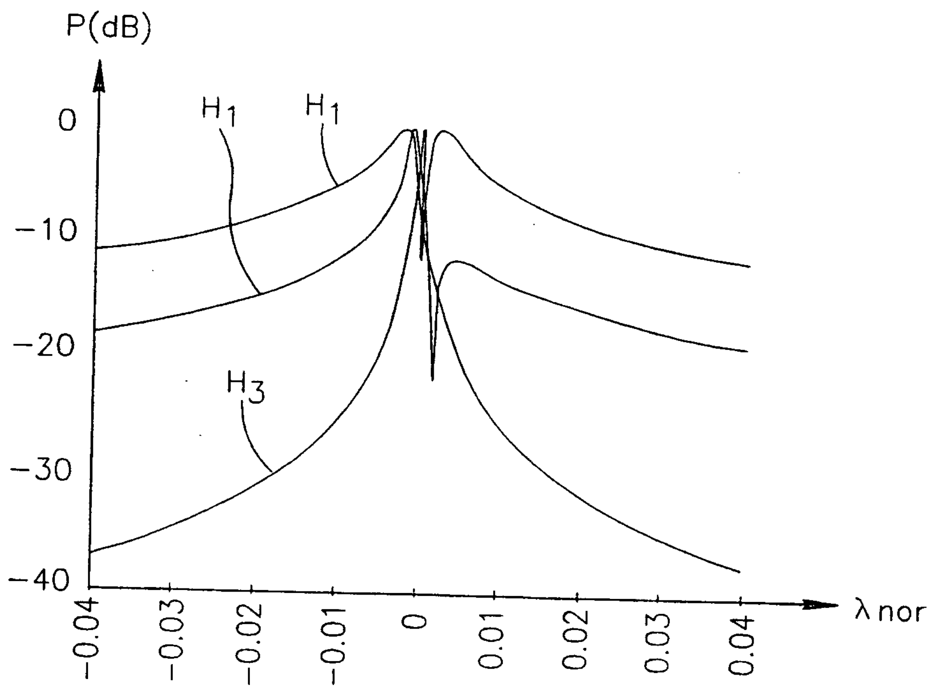
0.03
0.04
λ nor

FIG.4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−20
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H1
H1
H3
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0.03
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λ nor

FIG.5

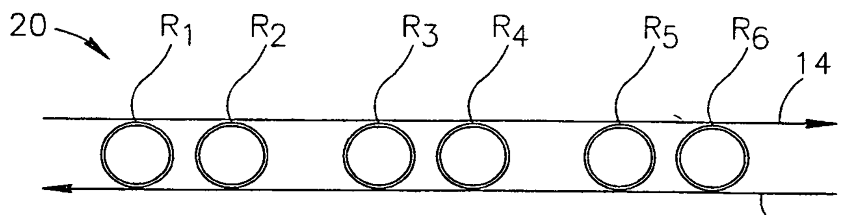

FIG.6A

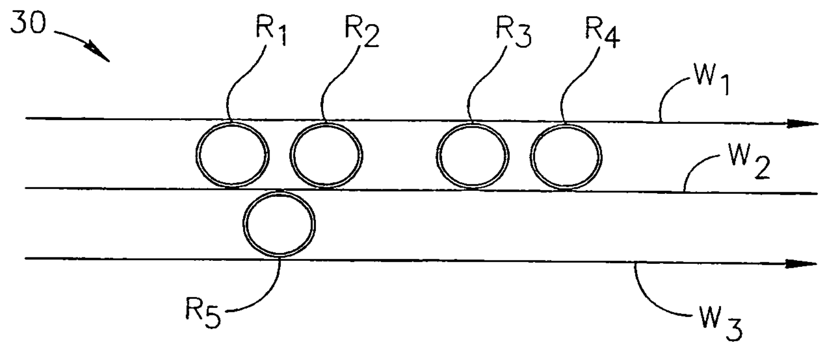

FIG.6B

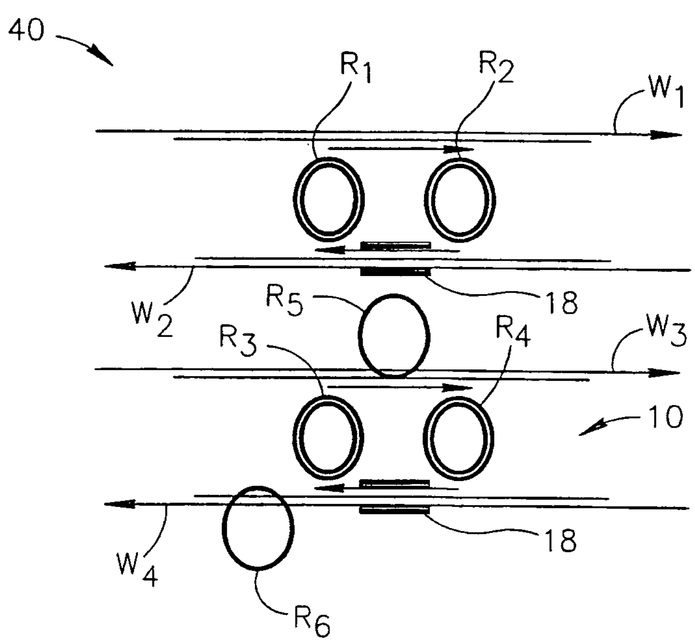

FIG.6C

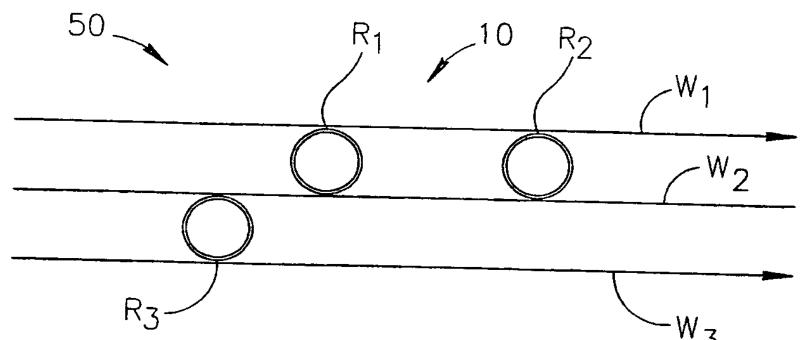

FIG.7A

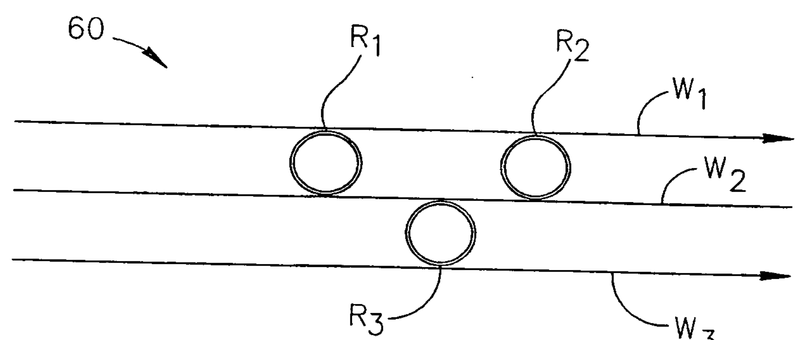

FIG.7B

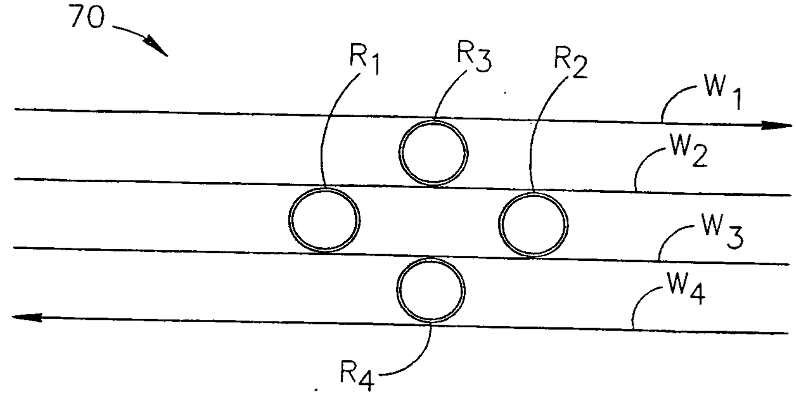

FIG.7C

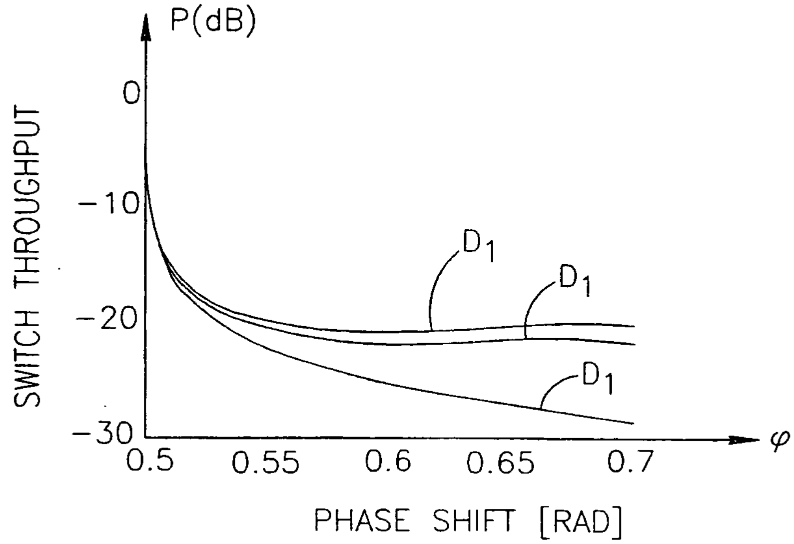

FIG.8

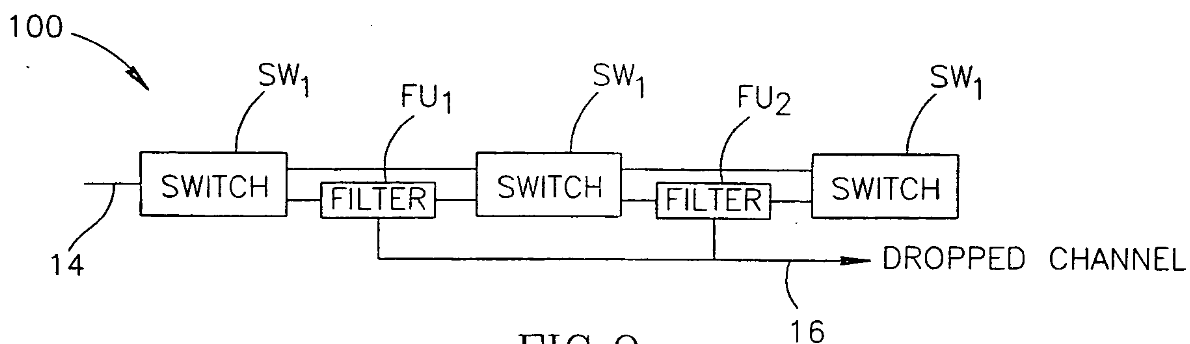

FIG.9

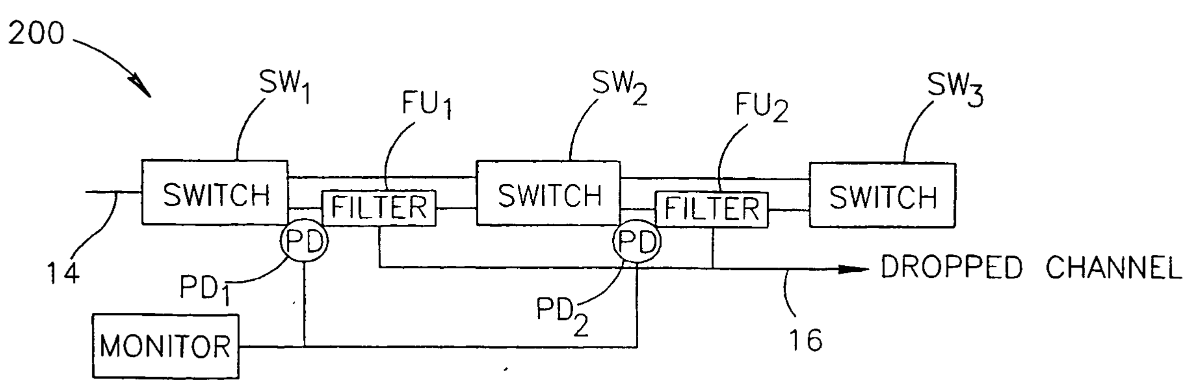

FIG.10

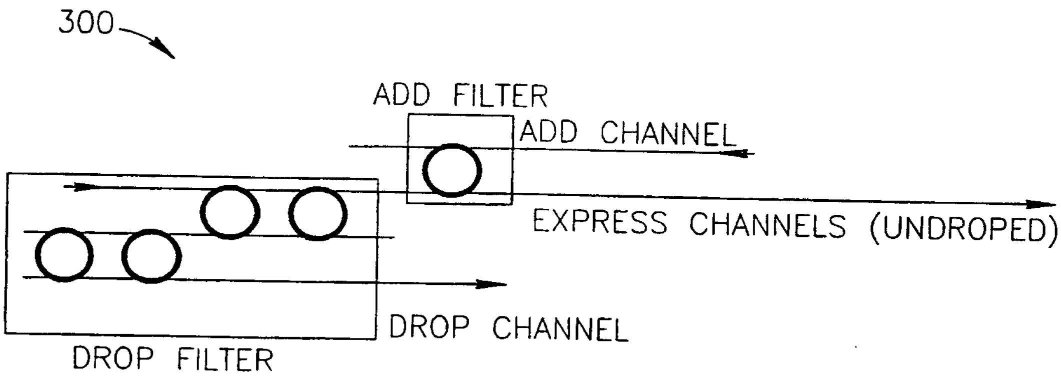

FIG.11A

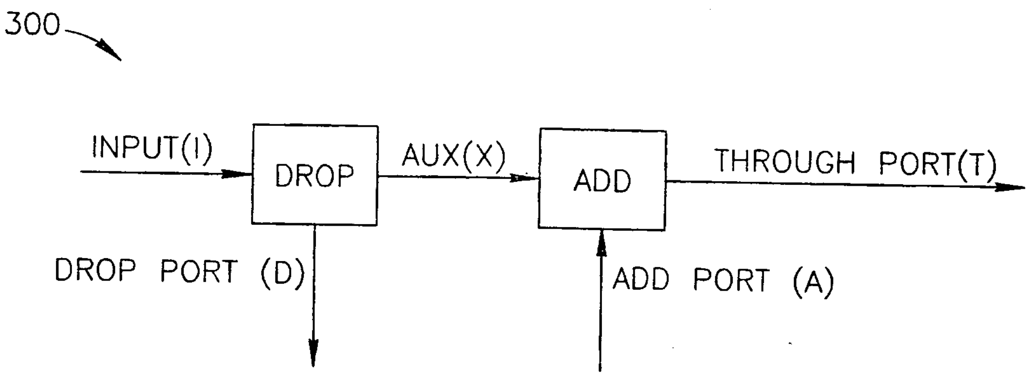

FIG.11B

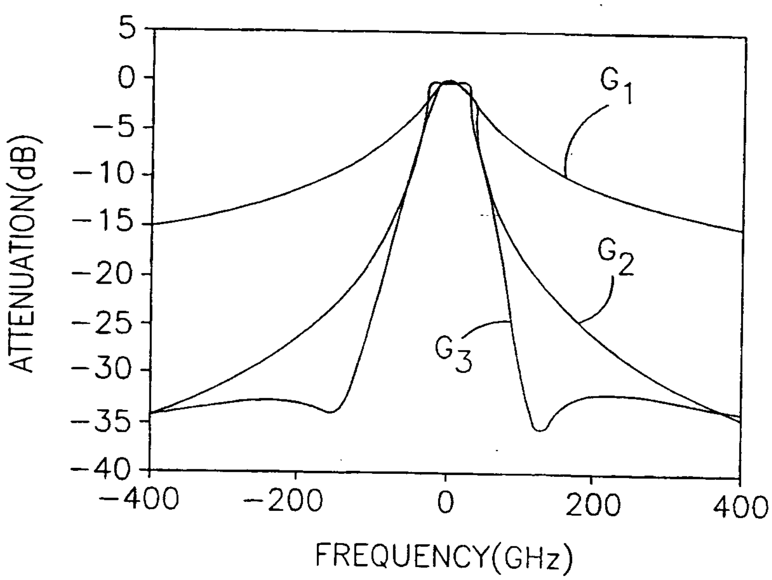

FIG.12

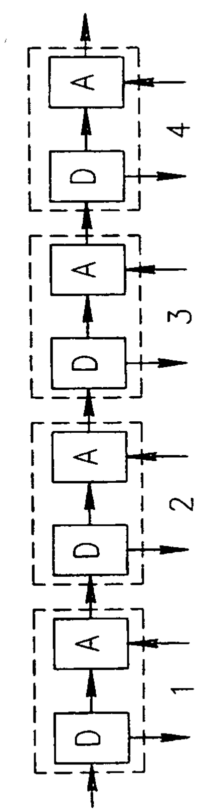
D
A
D
A
D
A
D
A
1
2
3
4

FIG.13

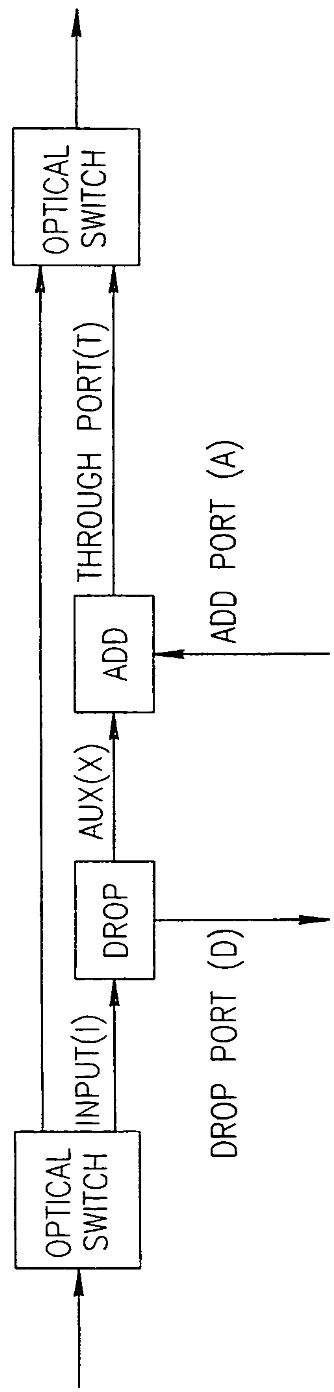
OPTICAL SWITCH
INPUT(I)
DROP
AUX(X)
ADD
THROUGH PORT(T)
OPTICAL SWITCH
DROP PORT (D)
ADD PORT (A)

FIG.14

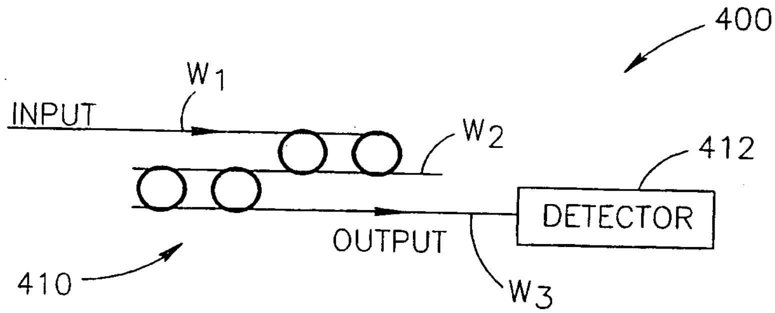

FIG.15

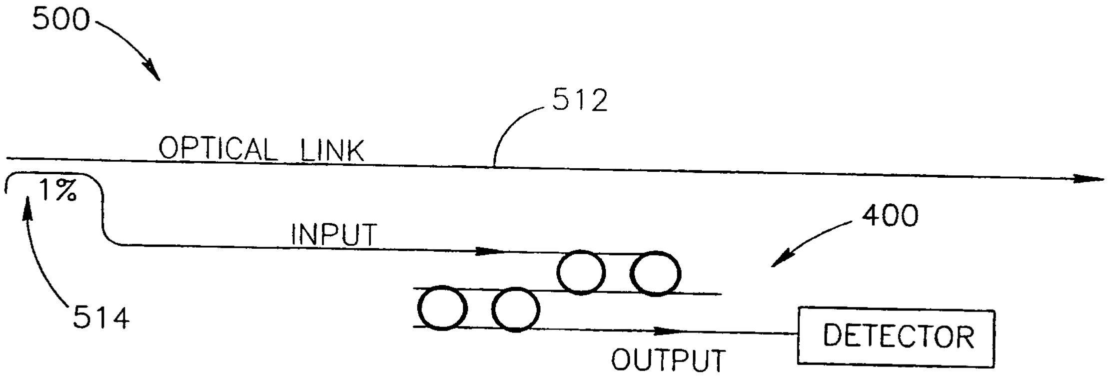

FIG.16

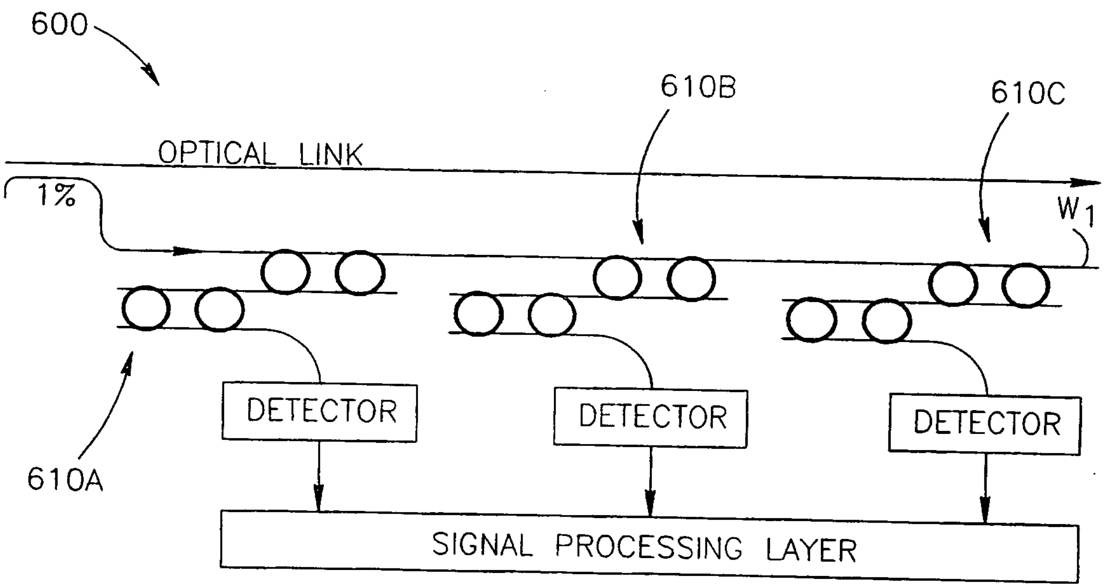

FIG.17

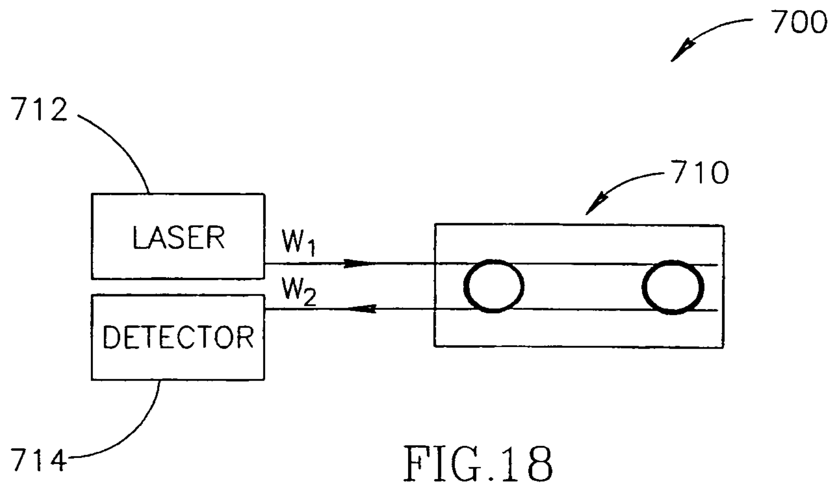

FIG.18

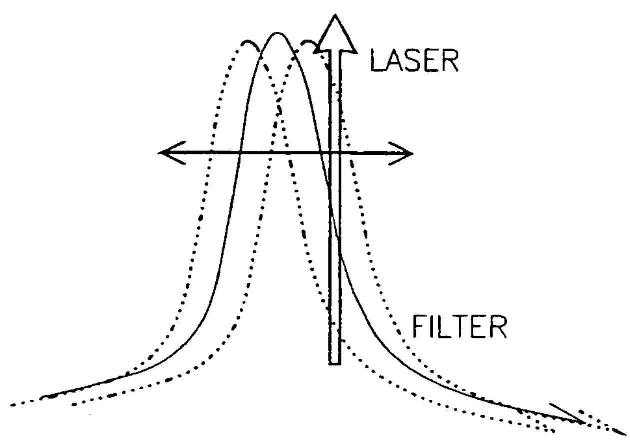

FIG.19

INTERNATIONAL SEARCH REPORT

International Application No
PCT/IL 00/00654

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 G02F1/313 H01S5/10 G02B6/12

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 G02F H01S G02B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

WPI Data, PAJ, IBM-TDB, EPO-Internal, INSPEC, COMPENDEX

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	LITTLE B E ET AL: "MICRORING RESONATOR CHANNEL DROPPING FILTERS" JOURNAL OF LIGHTWAVE TECHNOLOGY,US,IEEE. NEW YORK, vol. 15, no. 6, 1 June 1997 (1997-06-01), pages 998-1005, XP000700611 ISSN: 0733-8724 page 1000, right-hand column, line 29 -page 1001, left-hand column, line 26; figure 1B	1-3,12, 24-26, 29,30
A	WO 99 17151 A (MASSACHUSETTS INST TECHNOLOGY) 8 April 1999 (1999-04-08) cited in the application page 5 -page 8, line 7 page 9, line 8 -page 10, line 8; figures 3-7	1-4,6,8, 10-12, 15,19, 24,31,33

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[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
22 January 2001	29/01/2001

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Stang, I

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INTERNATIONAL SEARCH REPORT

Intern   nal Application No
PCT/IL 00/00654

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5 742 633 A (NOECKEL JENS UWE ET AL) 21 April 1998 (1998-04-21) column 4, line 32 - line 58 column 6, line 65 -column 7, line 50; figures 4,10-13	1-3,12, 13,17, 21, 24-26,31
A	GB 2 118 765 A (OUDAR JEAN LOUIS) 2 November 1983 (1983-11-02) page 3, line 95 - line 120; figures 5,6	1-6,8, 12,17, 24-26,31
A	US 4 775 214 A (JOHNSON LAWRENCE A) 4 October 1988 (1988-10-04) column 12, line 52 -column 14, line 38; figures 15-19	1,22,23
A	WO 98 57207 A (MASSACHUSETTS INST TECHNOLOGY) 17 December 1998 (1998-12-17) page 13, line 36 -page 15, line 18; figures 3,10	31,32

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

Intern ıal Application No
PCT/IL 00/00654

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO 9917151 A	08-04-1999	US 6052495 A	18-04-2000
US 5742633 A	21-04-1998	NONE	
GB 2118765 A	02-11-1983	NONE	
US 4775214 A	04-10-1988	NONE	
WO 9857207 A	17-12-1998	US 6130969 A	10-10-2000
		US 6101300 A	08-08-2000
		EP 0988569 A	29-03-2000